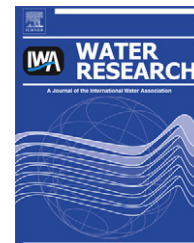


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Evolution of community-based arsenic removal systems in remote villages in West Bengal, India: Assessment of decade-long operation[☆]

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ABSTRACT

In Bangladesh and the neighboring state of West Bengal, India, over 100 million people are affected by widespread arsenic poisoning through drinking water drawn from underground sources containing arsenic at concentrations well above the permissible limit of 50 µg/L. The health effects caused by arsenic poisoning in this area is as catastrophic as any other natural calamity that occurred throughout the world in recent times. Since 1997, over 200 community level arsenic removal units have been installed in Indian subcontinent through collaboration between Bengal Engineering and Science University (BESU), India and Lehigh University, USA. Approximately 200,000 villagers collect arsenic-safe potable water from these units on a daily basis. The treated water is also safe for drinking with regard to its total dissolved solids, hardness, iron and manganese content. The units use regenerable arsenic-selective adsorbents. Regular maintenance and upkeep of the units is administered by the villagers through formation of villagers' water committee. The villagers contribute towards the cost of operation through collection of a small water tariff. Upon exhaustion, the adsorbents are regenerated in a central facility by a few trained villagers. The process of regeneration reduces the volume of disposable arsenic-laden solids by nearly two orders of magnitude and allows for the reuse of the adsorbent material. Finally, the arsenic-laden solids are contained on well-aerated coarse sand filters with minimum arsenic leaching. This disposal technique is scientifically more appropriate than dumping arsenic-loaded adsorbents in the reducing environment of landfills as currently practiced in developed countries including the United States. The design of the units underwent several modifications over last ten years to enhance the efficiency in terms of arsenic removal, ease of maintenance and ecologically safe containment and disposal of treatment residuals. The continued safe operation of these units has amply demonstrated that use of regenerable arsenic-selective adsorbents is quite viable in remote locations. The technology and associated socio-economic management of the units have matured over the years, generating promise for rapid replication in other severely arsenic-affected countries in Southeast Asia.

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[☆] Invited paper for the special arsenic issue.

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1. Introduction

Arsenic in the drinking water of millions of people living in different parts of the world has been a focus of attention for public health scientists and engineers (Bagla and Kaiser, 1996; Ng et al., 2003; Ravenscroft et al., 2005; Bhattacharya et al., 2007; Bundschuh, 2009). The arsenic crisis prevailing in the Gangetic delta extending over a large area of Bangladesh and India is arguably one of the worst calamities of the world in recent times (Chatterjee et al., 1995; Bearak, 1998). The crisis is slowly unfolding in Southeast Asia also, affecting several countries including Cambodia, Vietnam, Laos, Myanmar, etc (Berg et al., 2007; Stanger et al., 2005; Christen, 2001). The use of groundwater in these regions is favored by its easy availability, microbial safety and absence of proper infrastructure for treatment and distribution of surface water. Surface water is often contaminated due to the absence of proper sanitation practice. With growing populations and agricultural demand, excessive groundwater withdrawals have resulted in the dissolution of arsenic due to the geochemical weathering of minerals within the aquifer. The consequence of drinking arsenic contaminated water over a long period of time causes severe damages to the human body and often becomes fatal. While the best solution to the problem is to switch over to treated surface water which does not have any arsenic contamination, development and maintenance of surface water based drinking water system is expensive, time-consuming and investment-intensive. With all these difficulties, it is unlikely for a developing country to switch the source of water from groundwater to surface water in a short period of time. In order to save lives before such a changeover is possible, it is imperative to build arsenic removal systems on an emergency basis. Several arsenic removal technologies have been developed over the last two decades; some of them have gained wide-scale application in the field. A significant proportion of the technologies, if not all, use sorption onto innocuous hydrated metal oxides, the metals being iron, aluminum, titanium and zirconium (Bang et al., 2005; Driehaus et al., 1998; DeMarco et al., 2003; Dutta et al., 2004; Suzuki et al., 2000). Polymeric ligand exchange has also been demonstrated to be a viable sorbent medium for selective arsenic removal (Ramana and SenGupta, 1992). While the household treatment units are initially easier to install than the community-based system, the latter provides a more sustainable solution with a potential for economic growth. Since 1997, more than 200 community-scale arsenic removal units have been installed in the villages of West Bengal, a state of India neighboring Bangladesh. For all the treatment units, the villagers themselves take care of the maintenance, upkeep and management related to the units. In this article an account of the evolution of the treatment units is presented along with their performance for arsenic removal. The article also describes the extent and effect of community participation in this project.

2. Choice of scale of operation: domestic vs. community

During the first two years of the project beginning in 1997, both point of use (PoU) household units and community-

based well-head arsenic removal systems were installed. Note that while each PoU serves one family of villagers, nearly two hundred families collect potable water from each community-based arsenic removal unit. Also, arsenic being highly toxic, its removal must address the consequent disposal and/or containment issues. After thoroughly evaluating the pros and cons of both systems and their long-term sustainability for arsenic removal and containment, we pursued installation of only community-based well-head treatment units due to their following advantages:

- Regardless of the design of the PoU domestic unit, reliability of operation and quality control is necessary in terms of analyzing treated water for arsenic at some predetermined time interval. Frequent measurement and detection of arsenic in treated water is difficult and cost-prohibitive. For every single analysis of a water sample from a community-based unit, approximately two hundred water analyses would be required for individual household units, all other conditions remaining identical.
- Household PoU units using adsorbent media or coagulants will always generate arsenic-laden sludge or solids. Coordinating collection and safe disposal of sludge or used media from individual households poses a level of complexity and enforcement effort that are difficult to sustain in remote villages. The well-head community-based units reduce such management problems two hundred times.
- Even for household units, the villagers (mostly village women) need to come everyday to the existing well-head units to collect water. Thus, having a simple-to-operate arsenic removal system mounted on the well-head unit provides continued collective vigilance with regard to color (caused by iron), smell (due to biological activity) or other abnormal behaviors that may otherwise go unnoticed for household units.
- According to our estimate, both fixed and operating costs of the community-based well-head unit are significantly lower than the total sum of the same for two hundred household units. Also, it is relatively easy to introduce modifications and innovations in well-head units for performance enhancement through the collective and direct involvement of the community through a villagers' appointed water committee.

3. Design of the treatment unit

In rural areas of this geographical region, groundwater wells serve as the primary source of potable water. The wells for domestic water supply are fitted with hand pump mounted on top of it. According to an estimate, there are over 10 million such wells in the arsenic-affected area of Bangladesh alone (Kinniburgh and Smedley, 2001; Cheng et al., 2005). The arsenic removal units are installed at the top of the well and are attached to the hand pump. Fig. 1A is a photograph showing the usual method of collection of water. Fig. 1B is a schematic of the treatment unit along with the important

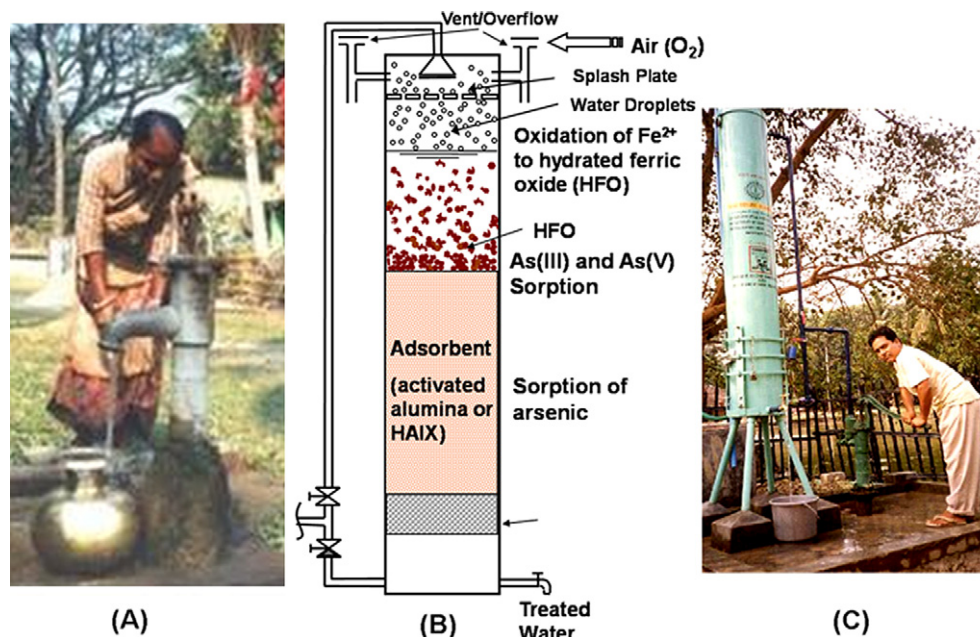
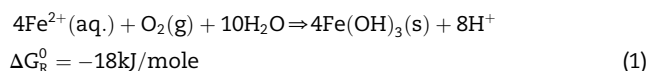


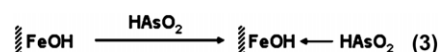
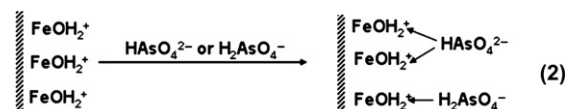
Fig. 1 – (a) Photograph of conventional method of water collection in remote villages in India (b) Schematic of the arsenic removal unit and (c) photograph of the treatment unit attached with arsenic contaminated well.

reactions taking place inside the unit and Fig. 1C shows a photograph of the treatment unit in use by a villager. The units do not require any electricity, addition of chemicals or pH adjustment for their daily operation. There was no change in the traditional method of water collection, an attribute which prompted instant acceptability of the treatment units by the users.

The community-scale arsenic removal unit essentially consists of a stainless steel column filled with about 100 L of adsorbent. The raw water inlet is located at the top of the column. Arsenic is removed from the contaminated water while it trickles down to the bottom of the unit from where the treated water is collected. The raw water inlet is designed with a spray head and splash plates so that small water droplets are formed at the entry point. Also, the top part of the column is designed with a large void space with vent connections that allow the air to get dissolved in the water droplets. The dissolved air helps oxidize the ferrous iron in the raw water to form fine precipitates of hydrated ferric oxide (HFO) according to the following reaction.



Oxidation of dissolved Fe(II) to insoluble Fe(III) hydroxide at near-neutral pH is a thermodynamically favorable process due to its relatively high negative free energy of reaction (ΔG_R^0) at the standard state (Morel and Hering, 1993). Freshly precipitated hydrated Fe(III) oxide (HFO) particle surfaces are considered to be a diprotic acid capable of forming the surface functional groups of FeOH_2^+ and FeOH at circum-neutral pH. HFO particles with these surface groups can selectively bind both arsenites or As(III) and arsenates or As(V) through formation of bidentate and/or monodentate inner-sphere complexes where Fe(III), a transition metal, serves as electron-



pair acceptor or Lewis acid (Dzombak and Morel, 1990): Commonly occurring anions present at relatively high concentrations, namely, chloride, sulfate and bicarbonate are weak ligands and exhibit poor sorption affinity to HFO particles (Dzombak and Morel, 1990). However, dissolved silica and phosphate compete against arsenic sorption (Meng et al., 2000; Roberts et al., 2004). Phosphate concentration in the groundwater region rarely exceeds 1.0 mg/L as P while silica concentration varies between 20 and 35 mg/L as SiO₂. A significant portion of influent arsenic is adsorbed by the freshly formed HFO precipitates inside the column. The remaining arsenic in the water is removed by a bed of adsorbent provided at the bottom part of the unit. The adsorbent bed packed with particles sized in the range 500–900 micron also helps to trap and retain arsenic-laden HFO particles (Sarkar et al., 2007). Groundwater in this area predominately contains dissolved iron in ferrous form [Fe(II)] in concentrations ranging from 2 to 10 mg/L. The design of the unit thus helps to exploit the presence of dissolved iron in raw water for arsenic removal through the oxidation and subsequent precipitation of HFO particles. At the same time, filtration of HFO particles and adsorption of arsenic as a polishing step

take place at the bottom part of the unit. Activated alumina which is a locally available low cost adsorbent with high affinity for As(V) species, has been used for most of the units. More recent installations also use another adsorbent, hybrid anion exchanger (HAIX) developed at Lehigh University (Sarkar et al., 2008).

The desired treated water flow rate from the arsenic removal unit is 10–12 L/min. The flow rate, however, diminishes over time due to the precipitation of the HFO particles within the bed. Backwashing of the column every other day to drive out the HFO particles is necessary to maintain a good flow rate through the column. The arsenic-laden HFO particles in the waste backwash are trapped on top of a coarse sand filter provided in the same location. The treatment units are robust and are fabricated locally with indigenous materials.

The adsorption column acts like a plug flow reactor and it is forgiving towards any occasional fluctuation in arsenic concentration in the influent feed water. These units consistently produce arsenic-safe water in a reliable manner. Also from a kinetic viewpoint, the selective sorption of trace arsenic is intraparticle diffusion controlled and the arsenic breakthrough curve is very gradual (Li and SenGupta, 2000). Therefore, analyzing the treated water once every month for arsenic concentration is adequate. Details of the equipment design and analytical techniques are available elsewhere (Sarkar et al., 2005).

4. Performance of the units

Depending on the arsenic and iron concentration in the raw water, the arsenic removal units produce on average about 1,000,000 L or 10,000 bed volume of treated water before the concentration of arsenic in the treated water exceeds the maximum contaminant level (MCL) which is currently set at 50 µg/L in India or Bangladesh. Once the arsenic concentration in the treated water exceeds the MCL, the exhausted adsorption media is removed from the unit and taken for regeneration at a nearby central regeneration facility. The operation of the arsenic removal unit is resumed with another adsorption media which is already regenerated. Fig. 2 represents arsenic breakthrough history of one such treatment unit located at Habra, West Bengal for over five cycles of operation. The unit is in operation since 2001 and uses activated alumina as adsorbent. The raw water had an average arsenic concentration of 140 µg/L. Although there was seasonal variation in arsenic concentration in raw water, it may be observed that it consistently produced arsenic-safe drinking water before the breakthrough took place. It may be noted that in each cycle of operation subsequent to regenerations, there was an initial leakage of arsenic but the overall volume of water treated for each run virtually remained the same. Also the arsenic leakage never exceeded the MCL.

Due to its unique design, the arsenic removal units are also capable of achieving a high degree of removal of dissolved iron present in the raw water. Iron is not a regulated element for safe drinking water, but is aesthetically displeasing. The units consistently provide water with iron content less than 0.5 mg/L Fig. 3 shows iron breakthrough history of the same arsenic removal unit in Habra, West Bengal. Routine

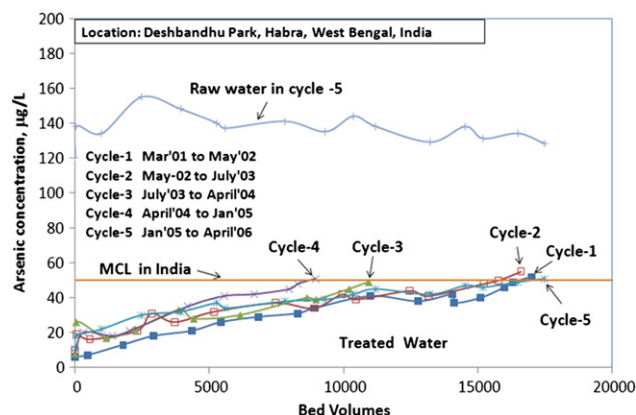


Fig. 2 – Arsenic breakthrough history of an arsenic removal unit at Habra village in West Bengal, India over five consecutive cycles of operation.

investigations revealed that the treated water is also safe for drinking with regard to its total dissolved solids, hardness and manganese content. Fig. 4 provides arsenic breakthrough history of another arsenic removal unit where a hybrid anion exchange resin (HAIX), developed in Lehigh University laboratory, was used in place of activated alumina as adsorbent. HAIX is known to be a better adsorbent compared to activated alumina and the underlying mechanism for its superior performance has been discussed elsewhere (Cumbal and SenGupta, 2005; Puttamraju and SenGupta, 2006). Under identical conditions, the length of column run for the units using HAIX is significantly longer compared to the units using activated alumina.

5. Evolution in design: two-bed adsorption units

The columns are routinely backwashed on alternating days to drive off the accumulated HFO particulates. This prevents the adsorbent bed from becoming clogged and any associated decrease in flow rate. The backwashing is done in up-flow

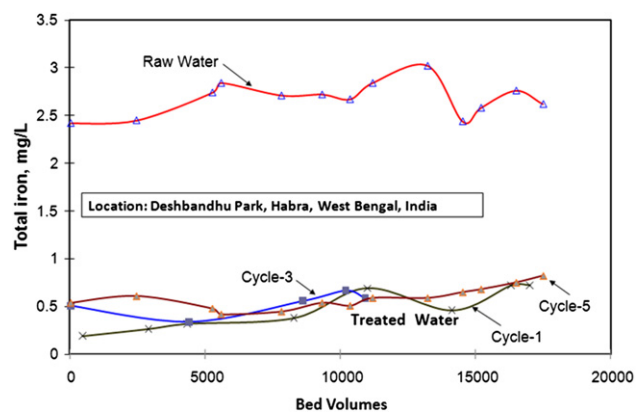


Fig. 3 – Iron breakthrough history of the arsenic removal unit at Habra village in West Bengal, India.

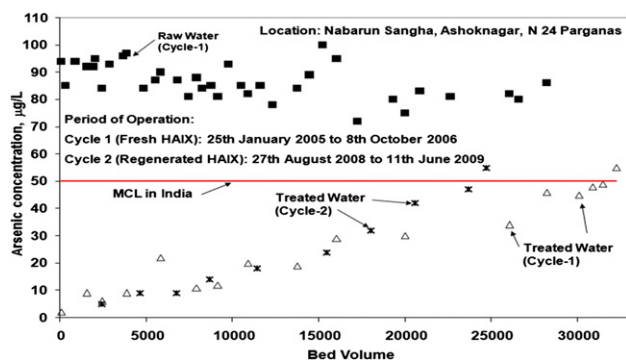


Fig. 4 – Arsenic breakthrough history for two cycles of an arsenic removal unit using hybrid anion exchange resin at Ashoknagar in West Bengal, India.

mode with the raw water entering from the bottom of the unit. The HFO has been observed to get deposited mainly in the top one-third section of the adsorbent bed. Hence, although significant amount of effort is required to do the backwashing, the bed does not get sufficiently fluidized and efficiency of backwash remains low. In order to overcome this difficulty, the single bed unit is split into two-bed design. The uppermost or the first column contains components necessary for oxidation of dissolved iron similar to the single-column unit; however, adsorbent media is activated alumina of volume of 50 L. The partially treated water then enters the second column containing 50 L activated alumina or HAIX, which basically acts as a polishing unit. Finally, treated water is collected at the bottom of the second column. Both columns have provisions for backwashing. However, the second column rarely requires backwash because all the oxidation of dissolved iron and subsequent precipitation occurs in the first column. The first column has a smaller height compared to the single-column design. Therefore, the backwashing is relatively easy and more effective. Fig. 5 provides a schematic of two-bed design. Fig. 6 represents the effluent breakthrough

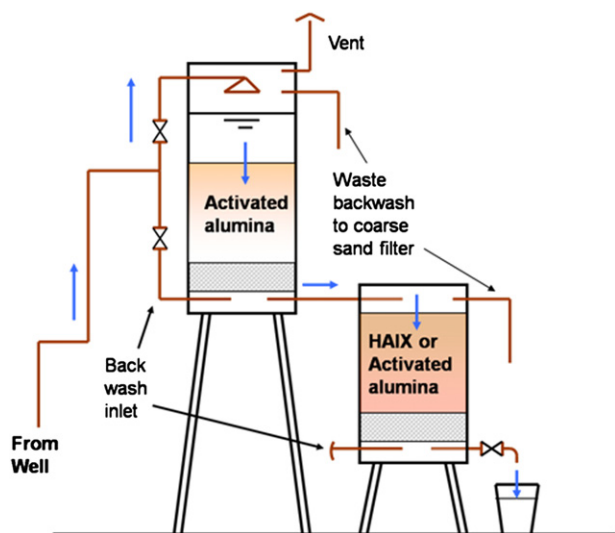


Fig. 5 – Schematic of the two-bed design of the arsenic removal units.

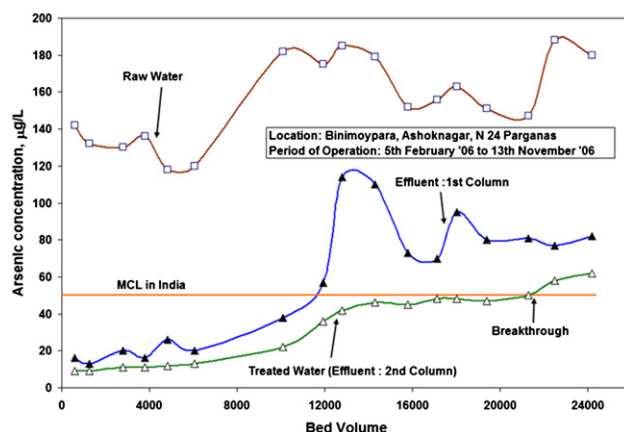


Fig. 6 – Arsenic breakthrough history for each bed of a two-bed type arsenic removal unit installed in West Bengal, India.

histories from both columns of one such unit located at Ashoknagar in West Bengal.

6. Regeneration of the exhausted media

Economy in operation is one necessary attribute for a technology to be acceptable to the masses in the developing countries. A significant amount of savings in terms of cost of

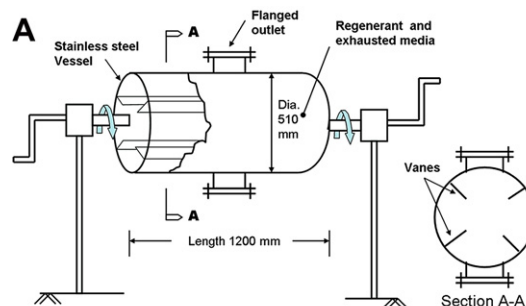
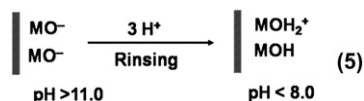
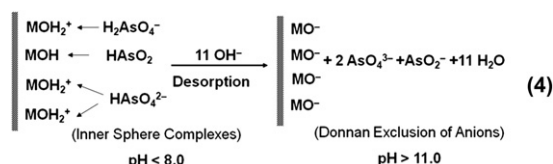


Fig. 7 – A. Schematic of the regeneration vessel used in the central regeneration facility. B. Photograph showing the trained villagers performing regeneration at the central regeneration facility.

treated water is possible when a regenerable adsorbent is used instead of one-time-use-only adsorbent. This design philosophy is particularly true when labor and chemicals, the two major resources required for regeneration, are relatively inexpensive in the developing countries. However, one prerequisite is that the regeneration procedure has to be simple and easy, so that even a group of trained villagers with little or no prior technical knowledge can effectively carry out the whole regeneration process. The regeneration protocol has been optimized over the last few years such that the cost of regeneration is one-fourth of the price of fresh activated alumina and one-sixth of HAIX.

Upon exhaustion of the adsorption column, media from the unit is replaced by fresh or already regenerated media. The exhausted media is taken to a central regeneration facility. Over one hundred batches of activated alumina and HAIX have been regenerated to date in the central regeneration facility by six trained members of the villagers' committee. An easy-to-operate stainless steel batch reactor is used for the regeneration process. Fig. 7A shows details of the regenerant vessel used during the last six years and the Fig. 7B shows the photograph of a regeneration process in progress carried out by trained villagers. Since each well-head unit uses approximately 100 kg of adsorbent, the individual regeneration steps have been streamlined and they are delineated in Table 1.

The primary reactions during regeneration of exhausted adsorbents with 2% NaOH and rinsing with dilute acid are presented below where M represents Al(III) or Fe(III) in AA or HAIX, respectively:



At high alkaline pH, the surface hydroxyl groups get deprotonated and negatively charged, thus causing very efficient desorption of anionic arsenic species due to the Donnan exclusion effect (Donnan, 1995). Subsequent rinsing with dilute acid allows formation of protonated surface functional groups with high arsenic sorption affinity. In addition to NaOH, the regenerant for HAIX also contained NaCl at a concentration of 2% to avoid poisoning of the anion exchange sites of the hybrid adsorbent by arsenate anions which are present at high concentrations in the spent regenerant solution.

Dissolved arsenic in the spent caustic regenerant varies from 30 mg/L to 100 mg/L and arsenic is present solely as arsenate or As(V). However, after mixing of waste regenerants, addition of Fe(III) chloride and subsequent adjustment of pH between 6.5 and 7.0, residual dissolved arsenic concentration promptly drops to less than 200 µg/L. The entire amount of arsenic present in the spent regenerant is essentially transferred into the solid phase along with ferric hydroxide precipitate, forming sludge of dry weight less than 1 kg. Thus, the residue left after the whole treatment process followed by regeneration is just a small volume of dried sludge of less than 1 kg in weight which can be easily handled and transported to suitable disposable facilities. In contrast, use of non-regenerable or one-time-use adsorbent would produce a treatment residual of about 100 kg arsenic-rich exhausted media which would pose a significant challenge for its safe disposal, especially in the rural settings of the affected area. Obviously, the management of the treatment residual would be much worse if the users, instead of using a community unit, each used household units that would produce treatment residuals from isolated and dispersed sources, thereby greatly enhancing the possibility of unsafe disposal of the toxic waste material. Community-scale units with regenerable adsorbent represent a sustainable approach thus preventing future crises from taking place.

It is worth mentioning that before 2004, all the community-scale units were used to be regenerated *in-situ*. Replacement of the earlier practice of regeneration *in-situ* by regeneration at central facility resulted in following improvements: 1) downtime for the maintenance of the units for regeneration/replacement of exhausted media has been reduced from two days to 2 h; 2) difficulty related to transport of regenerating equipment like pump and chemicals to the sites located at remote locations have been completely eliminated; 3)

Table 1 – Steps followed during regeneration of exhausted media and treatment of spent solutions.

Steps	Solutions used/obtained	Volume (L)	Time of contact/agitation (minutes)	Approximate equilibrium pH
I. Rinse with alkali	2% sodium hydroxide	140	60	12–13
II. Rinse with alkali	2% sodium hydroxide	140	60	12–13
III. Water rinse	Well water	100	15	12
IV. Acid rinse	0.5 N HCl	140	15	5–6
V. detoxification of spent regenerant	Treated spent regenerant ^a	≈ 520	60	6–7

a The spent regenerant and rinse solutions were collected and mixed together, FeCl₃ is added and pH is adjusted. After 60 min of contact time, the arsenic in the spent regenerants co-precipitated with hydrated ferric oxide. This resulted in total arsenic concentration in the supernatant to less than 200 µg/L.

negative impact of unreliable power situation has been eliminated; 4) better control over quality and efficiency of regeneration and subsequent waste management has been attained; and 5) sludge generation and storage at the sites dispersed over the region have been replaced by a centralized location of sludge generation and storage.

7. Containment of treatment residuals

In a community-based well-head arsenic removal system, arsenic-laden wastes evolve from two separate locations: first, arsenic-laden HFO particulates backwashed out every other day and collected on the top of a coarse sand filter located in the same premise; and second, solid treatment residuals formed at the central regeneration facility after the regeneration followed by stabilization. Chemically, these two wastes are similar; both are rich in iron and arsenic. Local environmental laws/regulations with regard to the safe disposal of arsenic-containing sludge in remote villages in the developing nations either do not exist or they are not enforceable. Thus, containing the arsenic removed from the groundwater with no adverse ecological impact and human health endangerment is as important as its removal to provide safe drinking water.

Previous investigations have reported that leaching of arsenic is stimulated or enhanced in a landfill or a hazardous waste site environment (Delemos et al., 2006, Ghosh et al., 2004). Both pH and redox conditions uniquely determine speciation of arsenic and iron that in turn control arsenic leachability. Fig. 8 shows the composite predominance or pe-pH diagram for various arsenic and iron species using equilibrium relationships available in the literature (Stumm and Morgan, 1996; Drever, 1988). The figure highlights (shaded

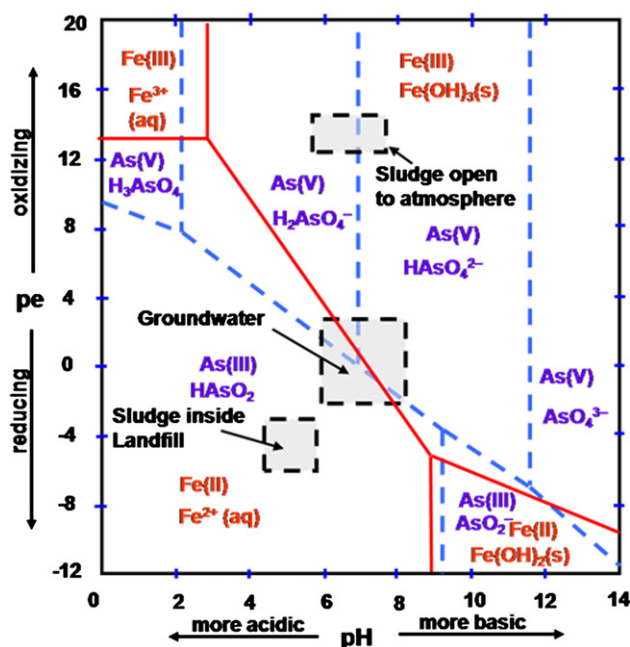


Fig. 8 – Composite predominance diagram for arsenic and iron species at different pe-pH conditions.

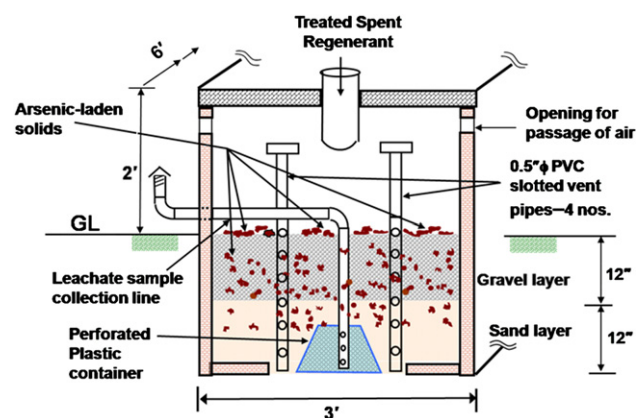
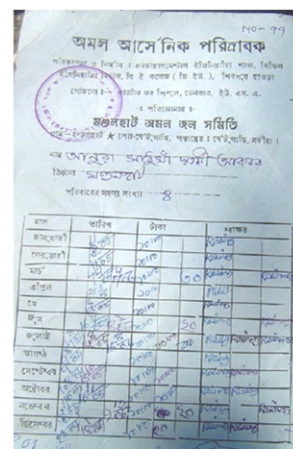


Fig. 9 – Schematic of an aerated coarse sand filter for containment of arsenic in the treatment residue.

rectangles) the three separate predominance zones of interest: Neutralized HFO sludge open to atmosphere, groundwater and the sludge inside landfill. Note that reduced and more soluble Fe(II) and As(III) are practically the sole

A



B

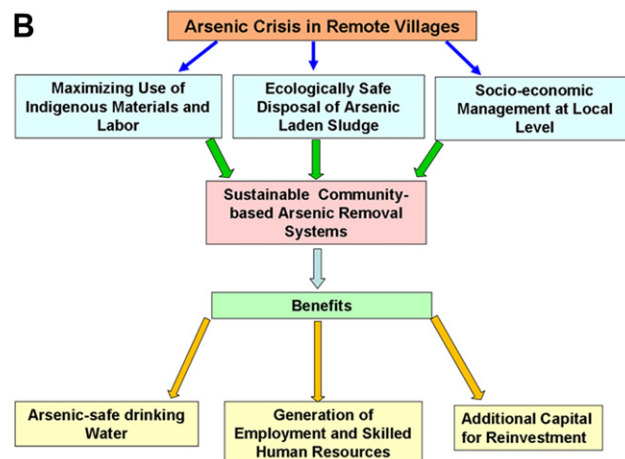


Fig. 10 – A. Photograph of a tariff card used to keep the records of payment in every month. B. Relationship between the input conditions for design of a community-based arsenic removal system and the benefits obtained thereof.

Table 2 – Different costs associated with the well-head arsenic removal unit.

Item No.	Item Description	Cost in Rupees	Cost in US Dollars
a. Fixed Capital Cost			
1	Stainless steel (SS-304) adsorption column with valves, internals, water meter and connections with the existing well-head hand pump	30,000	700
2	Adsorbent media: activated alumina	25,000	570
	* HAIX media		*1200
3	Civil work and installation including labor	5000	115
	Total	Rs. 55,000	\$1385
b. Maintenance Cost (Annual)			
1	Wage to the caretaker responsible for daily backwashing and minor maintenance	15,000	340
2	Water testing (once every month with a replicate) in Bengal Engineering College or any other private local laboratory	2500	60
	Total	Rs. 17,500	\$400
c. Cost of regeneration.			
1	Cost of once-a-year regeneration and spent regenerant treatment including labor and chemicals	Rs. 4500	\$110
d. Cost of water (per 1000 L) [based on operational cost]			
1.	Case-I. No Regeneration. Media replacement each year after 8000 BV (800,000 L) Activated alumina	Rs. 53.05	\$1.21
2.	Case-II Regeneration of media each year after 8000 BV (800,000 L)	Rs. 27.90	\$0.64

species inside a landfill environment where anoxic condition prevails. On the contrary, insoluble Fe(III) and As(V) predominate in the neutralized arsenic-laden HFO sludge under aerated condition. Thus, the arsenic-laden HFO sludge is more susceptible to rapid leaching under the anoxic condition like landfill than in the aerated condition.

The above scientific understanding led to the development of a simple yet effective way to dispose of the treatment residue. The low volume treatment residual is stored within a coarse sand filter chamber, the inside of which is kept well-aerated using vent pipes so as to avoid the development of anoxic conditions. Fig. 9 shows a schematic of the aerated sand filter for containment of arsenic. As the regeneration step allows over an order of magnitude reduction of the volume of treatment residual, the size of the coarse sand filter becomes adequate enough to store the contaminated waste at the same premise for decades without any significant arsenic leaching. Field testing of leachate collected at the bottom of the coarse sand filter confirmed that that it does not contain any significant concentration of arsenic.

Although the sludge resulting from the waste backwash water and the treatment of spent regenerant are chemically similar, the latter had significantly higher concentration of arsenic than the former. The total mass of arsenic contaminated sludge produced during each cycle of operation of an arsenic removal unit remained the same regardless of whether the unit is regenerated in-situ or at the central regeneration facility. However, the introduction of the practice of regeneration at a central location essentially helped avoiding the on-site storage of highly concentrated treatment residual generated from regeneration activity at each individual site. The leachate from the coarse sand filters at the central regeneration facility is regularly monitored for arsenic. Any accidental leaching of arsenic from the central storage due to onset of adverse environmental conditions can

therefore be quickly contained. Regular monitoring and risk management at individual sites located at remote places are difficult and almost impossible for the infrastructural conditions prevailing in the developing countries.

8. Management and economics of the community-scale units

Community participation was ensured at every stage of the installation as well as operation of the treatment units in this project. In each location, the villagers formed a water committee among themselves to take care of the management of the treatment unit. These committees include female members in every location. The regular maintenance of the unit is administered by caretakers appointed by the villagers' committee. The expenditures related to maintenance of the unit, monthly water testing, annual costs of regeneration, etc. are covered through the collection of a monthly water tariff from the users. In most places, a monthly water tariff of Rs. 15 (equivalent to 30 US cents) per family is adequate to cover the expenses related to the unit. The villagers' water committee manages the fund generated by depositing the money in a local bank. Fig. 10A shows a photograph of a tariff card used to keep the record of payments made every month. The users are regularly updated about the water quality, funds generated and issues related with the management of the unit. Fig. 10B summarizes the relationship among the input conditions of an arsenic-affected community; development of technology and the benefits accrued through the community-based project. The entire system has evolved as a viable business model where arsenic-affected villagers are also stakeholders of each unit installed.

Table 2 contains the details of capital and operation & maintenance cost of a unit. It also indicates the average cost of

treated water under two conditions: one with regenerable adsorbent and the other with one-time-use-only adsorbent. It may be noted that the difference in the cost of water tariff per month for the two cases is significant. The capital cost of the units has so far been provided by international and national funding agencies. The operating cost of the units is provided from the fund generated through the contribution of a monthly water tariff.

8.1. Closure

Currently more than 200 well-head arsenic removal units are in use in villages bordering eastern India and Bangladesh; no other viable source of potable water currently exists in these villages. Nearly 200,000 villagers routinely drink arsenic-safe water from these units that are run and maintained by a villagers' committee in every location. The three most significant technical features of the arsenic removal units are: first, the adsorbent media chosen are robust and regenerable; second, a central regeneration facility is adequately equipped to collect and regenerate exhausted media; and third, arsenic removed is contained as solids on aerated sand filters in an ecologically safe manner.

The units are economically sustainable. The villagers pay a small monthly tariff towards the cost of operation of the units. The technology and the associated socio-economic management of the units have matured over the last ten years to a point that rapid replication is possible in other parts of the world. Reported natural geochemical arsenic contamination of groundwater in Vietnam, Cambodia, Argentina and Mexico are characteristically similar to that in the Indian subcontinent; they all have significantly high dissolved Fe(II) concentrations (Berg et al., 2006; Del Razo et al., 1990). Similar community-based treatment strategies with active participation of villagers may go a long way in mitigating arsenic crisis in these countries.

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